COLLAPSIBILITY BEHAVIOUR OF ABS P400 AND PMMA USED AS SACRIFICIAL PATTERN IN DIRECT INVESTMENT CASTING PROCESS

MUHAMMAD SHAZWAN BIN SHUKRI

A thesis is submitted in
fulfillment of the requirement for the award of the
Degree of Master of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

AUGUST 2017

SPECIAL GRATITUDES TO:

MY BELOVED MOTHER,

Imilah @ Jamilah Binti Hasan @ Hassan

For her love, patience and support in my whole life

MY HONOURED SUPERVISOR,

Assoc. Prof Dr. Mustaffa Bin Hj. Ibrahim

For his generosity, advices, trust, support, patience and kindly guide me to complete this research

MY RESPECTED CO-SUPERVISOR,

Dr. Omar Mohd Faizan bin Marwah

For his guidance, advices and technical support

MY LOVELY FIANCE,

Adiba Rhaodah Andsaler

For her advices, moral support, patience and encouragement in this study

AND ALL MY COLLEAGUES,

For their help and support direct and indirectly, effort and motivation in this study

Lastly, may Allah bless you all and thank you.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to all those who gave me the opportunity and possibility to finish this thesis and my research especially to my beloved supervisor, Assoc. Prof Dr. Mustaffa Bin Hj. Ibrahim who has given advises and trusting me for this given title and kindly guide me to complete this research. Besides, a special thanks to my co-supervisor, Dr. Omar Mohd Faizan bin Marwah who has given motivation and support especially in the aspect of analysis work and thesis writing advises.

I would like to thanks to the Ministry of Education for funding this research under the Fundamental Research Grant Scheme (FRGS) vot 1423.

I would like to illustrate my sincere appreciation to those who had contributed directly and indirectly towards to the successful of this research project. I am deeply indebted to all additive manufacturing staff from Faculty of Mechanical and Manufacturing Engineering who had given very kind helps and invaluable guidance especially in experimental works and testing materials.

Moreover, I would like to give my special thanks to my fiance, Miss Adiba Rhaodah Andsaler who had fully supporting, gave advices, and encouraged me all the time throughout the whole process of this research work.

I would like to express my deepest appreciations to my mother Imilah @ Jamilah binti Hasan @ Hassan and family members who gave moral supports, encouragements, patience and love to enable me to complete this research.

ABSTRACT

The feasibility of the Investment Casting (IC) process has been choose to be vital route in producing the metal alloy products. However, less report regarding the feasibility of portable Additive Manufacturing (AM) machines to be employed in casting process. Sacrificial wax pattern in casting process has been substitute with the AM material due to its brittleness and higher cost for hard tooling. Due to this constrain, the quality of fabricated AM materials, collapsibility analysis and strain induce was investigated. The patterns were made using ABS P400 and PMMA materials by two different types of technique which are Fused Filament Fabrication (FFF) and Polyjet technique. There were three different types of internal structures which are hollow, square and hexagon patterns. The thermal properties of the materials were studied by thermogravimetry analyzer (TGA) and linear thermal expansion. The collapsibility screening was determined to investigate the behavior of the patterns underneath the expansion. Apparently, patterns made by Polyjet technique shows better accuracy compare to FFF technique. It shows that, the PMMA error lies between -2.2 % until -0.63 % compared to ABS which is -2.4 % until 1.2% for hollow, square and hexagon patterns respectively. The data of the surface roughness were varies whereas internal structures does not play significant role in improving the surface roughness. From the strain analysis, it can be suggested that hexagon internal structure yield less stress compare to square patterns. In terms of collapsibility, hollow and hexagon patterns yield most successful warping whereas it indicates the patterns able to collapse underneath the expansion. Moreover, PMMA material tends to gain higher strain compared to ABS material whereas this can be illustrated by the graph of linear expansion. Nevertheless, to overcome the cracking of ceramic shell due to higher thermal expansion, different build layer thickness was adopted to overcome the issue.

ABSTRAK

Kesesuaian proses tuangan deras (IC) dipilih sebagai satu kaedah untuk menghasilkan produk berasaskan logam. Tetapi, kurang laporan mengenai kesesuaian mesin serbaguna bahan pembuatan tambahan (AM) digunakan dalam proses tuangan deras. Acuan lilin telah ditukar ganti dengan AM kerana acuan lilin mempunyai sifat rapuh dan kos yang tinggi untuk acuannya. Disebakan oleh kekangan demikian, perkara yang telah dikaji adalah merangkumi kualiti bahan pembuatan tambahan (AM), analisis keruntuhan bahan dan juga daya terikan bahan. Corak bahan telah dibuat menggunakan bahan ABS P400 dan PMMA menggunakan dua teknik iaitu pembuatan filamen bersatu (FFF) dan juga teknik Polijet. Terdapat tiga jenis struktur dalaman iaitu berongga kosong, segi empat sama dan juga heksagon. Kajian haba bahan telah di kaji menggunakan Thermogravimetric Analysis (TGA) dan juga pengembahan haba selari. Keruntuhan bahan telah di kaji untuk mengetahui tindakbalas corak dibawah pengembahan bahan. Secara jitunya, corak yang diperbuat daripada bahan PMMA menampilkan ketepatan dimensi lebih baik berbanding teknik FFF. Seterusnya, ralat bahan PMMA terletak di antara -2.2% sehingga –0.63% manakala bahan ABS terletak di antara -2.4% sehingga 1.2% untuk berongga kosong, segi empat sama dan juga heksagon. Data untuk kekasaran permukaan pula adalah berbeza dimana bentuk struktur dalaman tidak memainkan peranan yang penting dalam meningkatkan kualiti permukaan bahan. Daripada analisis terikan, dilihat bahawa struktur bentuk heksagon menghasilkan daya tekanan yang kurang berbanding bentuk segi empat sama. Dalam aspek kerapuhan bahan pula, corak rongga kosong dan segi empat sama menghasilkan keledingan iaitu corak tersebut berjaya untuk menahan daya pengembahan. Tambahan pula, bahan PMMA mengalami daya terikan yang besar berbanding bahan ABS dimana ia dapat dilihat melalui graf pengembangan selari. Walaubagaimanapun, untuk mengatasi permasalahan keretakan seramik disebabkan faktor pengembangan haba yang tinggi, pelbagai lapisan ketebalan seramik telah digunakan.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOL AND ABBREVIATION

α	-	Type I error (α risk)
β	-	parameter
°C	-	Degree celcius
µm	-	Micrometer
K	-	kelvin
ΔL	-	Change length in speciment
ΔT	-	Temperature change during test
ΔX	-	Dimensional deviation
3DP		3D Printing
ABS		Acrylonitrile butadiene styrene
AM		Additive manufacturing
ASTM		American standard testing method
CAD		Computer aided design
CMM		Coordinate measuring machine
CTE		Coefficient thermal expansion
DIC		Direct investment casting
DA		Dimensional accuracies
FDM		Fused deposition modelling
FFF		Fused filament fabrication
IC		Investment casting
ISO		International standard organization
LM		Layer manufacturing
LT		Layer thickness
LOM		Laminated object manufacturing
MJM		Multijet modelling
MM		Model maker
PO		Part orientation

PMMA	Poly methyl methacrylate
Ra	Roughness accuracy
RP	Rapid prototyping
RM	Rapid manufacturing
RIC	Rapid investment casting
RT	Rapid tooling
Rv	Void ratio
SR	Surface roughness
SLA	Stereolithography
SLS	Selective laser sintering
STL	Stereolithography file
Tg	Glass transition temperature
UV	Ultraviolet

CHAPTER 1

INTRODUCTION

1.1 Research Background

Investment Casting (IC) is considered as a feasible method to substitute conventional manufacturing process regarding its advantages in producing near net shape of metal with economical of mass production. Conventional method of IC using traditional wax material as a sacrificial pattern has been preferred as the expendable material which can be reused after dewaxing process as well as reducing the materials cost. Despites its advantage in reducing the cost, there is a limitation in which producing the precision casting of metal whereas the wax material easily breaks and warps due to its brittleness properties. Thus, for requirement in precision thin wall casting which is need to be dipped into the slurry coating to develop deposition of ceramic shell molds, it is not recommended. In addition, using the wax as sacrificial pattern has encountered major problem such as slow processing development of new pattern mold in which results in expensive cost and longer total lead time process (Dickens *et al.*, 1995). Hence, it is not suitable for low volume casting production whereby longer lead time and high cost are the main concern factors. For instance, the high cost is determined by number of labours, price of refractory and binder materials as well as durable of mould fabrication. Elimination of hard tooling for wax pattern essentially needs justification in order to align with the low volume of production.

Therefore, Additive Manufacturing (AM) has inspired many manufacture industries in providing variations of perspective in IC process. This technology benefits the designer to produce a 3D part directly from the Computer-Aided Design (CAD) data more frequently without additional lead time. The fabricated prototype patterns are used for evaluation assessment with the valuable impact of perception especially for tool making or early optimization of concept designs. The ability of producing smooth surface, better dimensional accuracy and complexity shape have taken AM technologies one step ahead from wax pattern. Henceforward, IC industry has taken these advantages of using AM technologies to produce the sacrificial pattern either by direct or indirect approaches.

Concurrently, there are several types of AM techniques that offer robustness in terms of patterns fabricated in which to be employed in IC process. Major techniques of AM such as Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Laminated Object Manufacturing (LOM), Multijet Modeling (MJM) and Three Dimensional Printing (3D-Printer) have been explored its achievability in producing sacrificial patterns (Marwah *et al.*, 2012). Generally, utilization of AM parts in interchange of the conventional wax pattern has beneficial in substantial lead time, effective cost, excellence quality and turn into essential tool for fabricating new product design. Subsequently, implication of AM has speed up the lead times of production from virtual to physical prototyping. Regarding its proficiency to produce pattern, AM has a few potential issues that many researchers encountered since years ago. The issues regarding the quality of the pattern are shrinkage and wrapping which need a full consideration. In this case, early optimization of parameters should be implant in order to enhance the quality of the fabricated AM part (Sabau, 2007).

Nowadays, the advancement of Additive Manufacturing (AM) technology has develop a world most precise, cost-effective and portable AM machine such as portable 3D Printing which has same capability as full large scale high end AM machines. These machines works effectively in producing a full scale 3D prototype by depending on the types of materials used, commonly ABS and PLA. Most of the available portable 3D printer in market are based on the concept of Fused Deposition Modeling (FDM) which simply known as Fused Filament Fabrication (FFF) in which a process by a machine deposits a filament of a certain material on top or next to the same material, in order to create a joint by heat or adhesion. Moreover, another 3D technology which is capable of producing physical pattern which has precision dimension as well as smooth and transparent surface is Polyjet 3D Printer system. This system works on concept of similar to inkjet printing, but instead of jetting drops of ink onto paper, PolyJet 3D Printers jet layers of curable liquid photopolymer onto a build tray. Nevertheless, there are fewer reports regarding the quality of end product produce by portable 3D machines and the feasibility to be used as sacrificial pattern in IC process. Hence, in this study, it is essential to determine the competency of printed pattern by portable 3D machines to be used as sacrificial pattern in IC process.

On the other hand, occurrence of cracking of shell mold is major problem for non-wax materials such as Acrylonitrile Butadine Styrene (ABS) from FDM. Consequently, the reconstruction of internal pattern structures have been effectively and aggressively studies to solve the issue regarding the cracking of ceramic shell moulds (Norouzi *et al.*, 2009). Stresses induced by pattern expansion during burnout process are major problems resulting in shell cracking. In addition, most of researcher focused on different internal structure patterns especially on Stereolithography (SLA) process. Thus, less reports regarding the materials used by portable 3D printer based. Besides, the Coefficient of Thermal Expansion (CTE) is one of the major issue need to be fully understand and study in order to reduce the effects of shell cracking (Wang *et al.*, 2010). Furthermore, the glass transition temperature (Tg) also is comprehensive in determining the cracking of the ceramic shell molds and it is significant than CTE of plastic materials (Wang & Shih, 2010).

1.2 Problem statement

Conventional IC using wax as sacrificial pattern is favored to be a solid method in producing high precision casting metal. Nevertheless, conventional IC patterns made from wax have properties that limit its application in precision casting especially for parts with thin geometries. The parts usually tend to break or deform when handling or dipping in the refractory slurry (Wang *et al.*, 2010). Furthermore, it is not economical when producing small quantity parts of casting by using the injection moulding wax as a sacrificial pattern (Chua *et al.*, 2005). It is believed that the downside of conventional wax process essentially required die making for processing the patterns in which contributed to the higher cost and longer lead time and makes the method unsustainable.

Many studies have been conducted to substitute the conventional method by implanting the AM technology in IC process. However, most of the studies have circulated on the feasibility of the high-end AM machine such as FDM, SLA, SLS and MJM using different materials to substitute wax pattern as sacrificial pattern in IC process. There is less reports regarding the possibility of portable AM machine to fabricate as sacrificial pattern for IC process. In addition, there is also less report regarding the study of comparison between ABS P400 and PMMA based materials pattern fabricated by portable FFF technique and Poly Jetting technique respectively. The issue such as staircase effect is the main reason that affected the quality of pattern made by AM technique. This issue indirectly affect the quality of casting parts such as dimensional accuracy and surface roughness and need to be addressed continuously (Cheah *et al.*, 2005). Moreover, there is less report regarding the quality of part produce by portable AM machine in terms of dimensional accuracy and surface roughness that associated with IC process.

For the non-wax pattern applicable in IC process, it revealed that ceramic shell cracks due to excessive thermal expansions, incomplete collapsibility of pattern during burnout, residual ash and poor surface finish. Most of AM materials used for sacrificial pattern in IC process have CTE values larger than ceramic materials in which induce significant amount of stress on ceramic shell. In IC process, shell cracking occurs when the rupture temperature of the ceramic shell is lower than the glass transition temperature of the pattern material and internal web-link buckling temperature (Yao & Leu, 1999). The cracked occurs when the stress induced in the ceramic shell is greater than the Modulus of Rupture (MOR) of the pattern material. Due to this phenomenon, there are reports regarding the internal built structures for SL process and the hollow internal structure has been employed to decrease the stress and improve pattern drainage. However, research on the different inner structures patterns for portable FFF technique and portable Polyjet technique were still lacking.

1.3 Objectives of the Study

The objectives of this study are as follows:

a) To study the dimensional accuracy and surface roughness of ABS P400 and PMMA patterns made by portable AM machines that used in direct IC process.
b) To investigate the three different internal structures which are hollow, square and hexagon patterns collapsibility in IC process.
c) To analyse the rate of shell cracking during burnout process.

1.4 Scope of the Study

The accomplishments of study based on several scopes such as:

a) The fabrication of three different internal structures such as hollow, square and hexagon patterns for ABS P400 material using portable FFF 3D printer (Odyssey X2) and PMMA material using Polyjet 3D printer desktop (Object 30 Pro).
b) The three different internal structures of fabricated AM parts were evaluated including dimensional accuracy and surface roughness.
c) By using TGA and DTA to determine the thermal properties.
d) Feasibility of strain gauge for detecting the strain induce on the patterns and the ceramic shell moulds.
e) Screening the patterns collapsibility behaviour during the burnout process using Protherm furnace ranging temperature in between 30 ℃ to 150 ℃.
f) The sacrificial patterns are based on the AM part shapes and size.

1.5 Significance of study

Enhancement of new application, invention and adaptation on an existing design tool will boost the improvement of quality production. Therefore, the study on the pattern development of AM application by implanting patterns as direct sacrificial pattern in IC is essential as it beneficial in elimination of hard tooling. Diversification of techniques in AM has been explored to minimize space thoroughly and able to generate diverse solutions in IC process. Intensification of AM technique currently pays attention to portable 3D Printer techniques which is currently economical. The fabrication of AM patterns in which requires high intricacy and low mass casting in IC is the key to significant reduction of total lead time and cost effective of manufacturing.

It is expected that the outcome of the study will be an abundant support to the IC manufacturer whereby 3D Printer technologies (portable FFF 3D printer and Polyjet 3D printer) are applied in production of pattern whereby it contributed to effective of metal casting parts. Therefore, direct IC routes by portable AM machines works efficiently whereby lower cost, fast fabrication of patterns as well as enhancement of quality products are the main criteria to be concerned.

1.6 Summary

This chapter presents the introduction of this study which is vital of implementing the AM method in the IC process. Besides, it also present the research background of this study whereas involved the conventional IC process, AM methods and relation of AM in IC process. Furthermore, it shortly discusses the vital problem about this study. In addition, the significant objectives and scopes of this study were mentioned in this chapter. In the end of this chapter, it discuss about the significant of this study towards community especially in demanding industries.

.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter particularizing few aspects such as potential of Investment Casting (IC) process, disadvantage of conventional IC process, Additive manufacturing (AM) process and the feasibility of pattern produce by AM process to be used as direct sacrificial pattern in IC process. At the end of this chapter, it be a summarization of different aspects regarding the related perspective views on this study.

Upon the modernization of the world of technology, AM has emerged the substantial contribution in manufacturing industry specifically in fabrication of prototypes pattern or significantly as end product. Due to the stresses in terms of high cost, longer lead time as well as larger quantity of materials usage, once again AM provides a significant solution regarding elimination of tooling and substitution of expandable wax pattern. This study concentrate on the feasibility of AM process in which produce a direct sacrificial pattern in IC process. Thus, a full review on viability of AM process and IC process discussed on this chapter.

2.2 Conventional Investment Casting

The advancement in the nature of the industry has driven the process to be named as lost wax process whereby the physical properties of wax itself can be shaped into anything. Since the early days of introduction of this technology, wax has been preferred as important material to be shaped according to desire end products.

The lost wax process is favored by the name of Investment Casting (IC) process whereas the process can produces high tolerance of casting, good dimensional stability as well as near net shape of end products for most metal which can be categorized as ferrous (commonly stainless steel, tool steel and carbon steel) to non-ferrous alloy (commonly aluminum, brass and copper) (Horton, 2008). IC is ideal for applications that have relatively low production quantities (10 to 10000 pieces) or rapidly changing the product designs. In addition, IC is the most familiar method of metal fabrication that has been used for several centuries.

Basically, IC process requires a sacrificial wax pattern in which have same geometrical shape, design and scale as the final metal cast part. In this casting technique, a pattern, usually made of wax, is utilized in forming the inside cavity of a refractory mould. The pattern is formed by injecting the molten wax into a permanent mould of the desired shape and there by cooling it until solidification. In the ceramic shell method, the pattern is gated to a wax sprue. Then the sprue pattern are invested with ceramic slurry which is then solidified forming a mould around the wax pattern. The wax pattern is then removed from the mould by melting or burning. The subsequent refractory shell is further hardened by heating and then filled with molten metal to produce the finished part (Bemblage & Karunakar, 2011).

The working efficiency of investment casting depends largely upon the quality of the disposable pattern since its surface and dimensional characteristics are transferred to the ceramic shell and also to the final casting. Wax is the most widely used pattern material but blends containing different types of waxes need to be modified in terms of their properties through the addition of some materials called additives and fillers (Bemblage & Karunakar, 2011). Nowadays, this technique rapidly used in producing high complexity geometry shape, high temperatures application as well as lightweight metals such as aircraft engine, turbine blade, medical instrument and so on (Vasconcelos *et al*., 2002). Figure 2.1 shows the flows of conventional IC process.

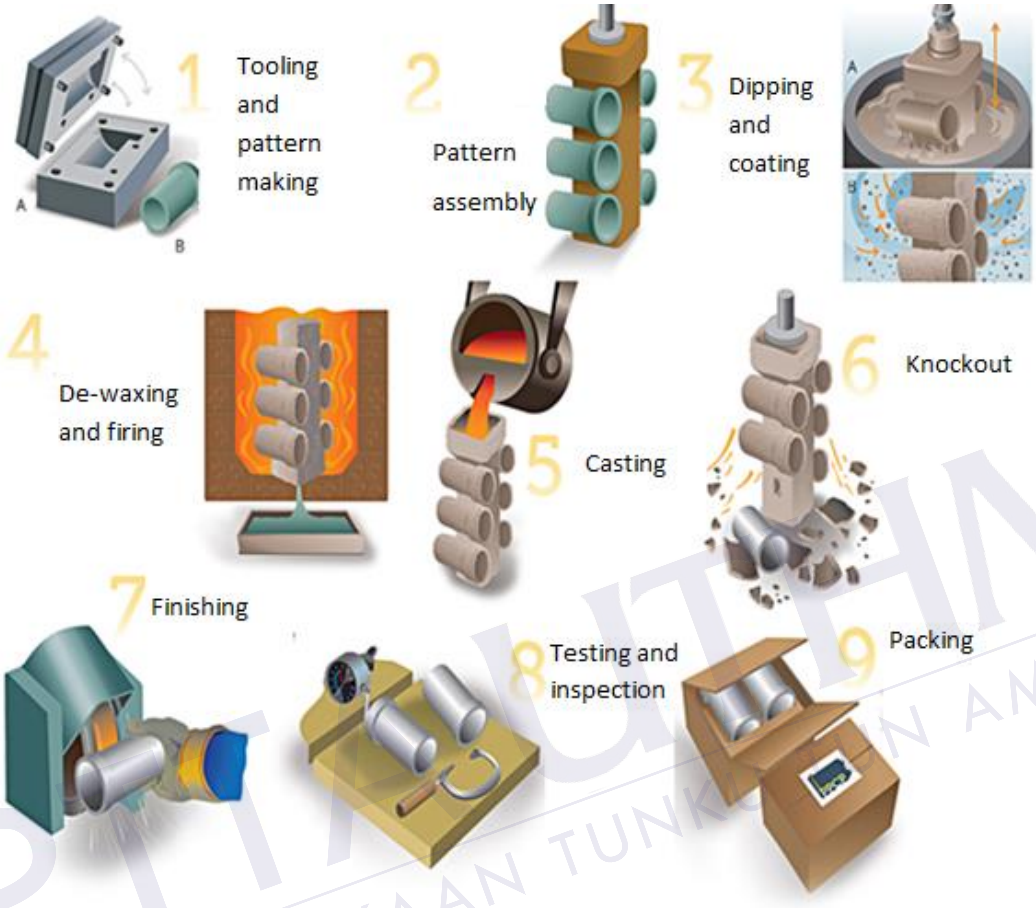

Figure 2.1: Overview of IC process (Tedds, 2013)

2.2.1 Constraints of Investment Casting Process

Despites its ability to produce an intricate design of metal part, IC suffer constrains in terms of cost and lead time. Conventional IC principally depending on the wax pattern for the fabrication of ceramic mold pattern, thus, there is necessity of tool for injecting the wax into desire shaped. In this case, the tooling for the injecting wax is the limitation of IC process due to the high cost of production and lead time as well as not effectively in changing the product designs. As mentioned by Ding (2004) there is about 70 % of total lead time when producing the initial tooling of new pattern depending on the complexity of the design shape. In addition, conventional IC process undergoes longer total lead time due to the fabrication of injection wax tooling approximately 13 - 21 weeks. However, the total lead time will increase if there is flawed on the pattern tools in terms of dimensional accuracy (Jacobs, 1995). Figure 2.2 shows the total lead time for IC process.

Conventional Investment Casting	CAD Design or mold	Mold fabrication	Wax pattern injection	Ceramic shell	Pattern removal	Pre-heating firing	Casting	Knockout ●Finishing
	3 weeks	6-14 weeks	4 weeks					

Total lead time = 13-21 weeks (approx.)

Figure 2.2: The total lead time of IC process

The application of IC with wax pattern has been favored by many manufactures as it provides good surface finish and near net shape of final metal products. Nevertheless, when making a hard tooling of wax pattern it involves with high cost fabrication as well as lead time process, thus, it is not efficient for a single or low volume production (Sivadasan & Singh, 2013). These perspectives are driven by two main factors such as requirement of hard tooling and longer lead time process for tooling itself. These factors affected the chain process of IC when a low volume of production is essential. In terms of fabricating the sacrificial patterns, the hard tooling for injection moulding process is needed to produce desired sacrificial wax pattern in which leading to cost justification. Besides, mould designer commonly face few problems when undertaking some adjustment on the hard tooling pattern such as precise dimension, alteration of designs and defects on design mould. Therefore, the total time for hard tooling significantly increase due to intricacy of designs as well as modification on the designs (Ferreira *et al*., 2006).

The needs of hard tooling in IC process must be eliminate without concerning the hard tooling cost and lead time process in order to fabricate low volume production effectively. Furthermore, low volume production suffers high tooling cost and expensive wax pattern moulding fabrication, thus it prefers for mass production (Cheah *et.al*., 2005). The inception of IC process without hard tooling has encouraged the application of AM technology to develop a low volume production

REFERENCES

3D PRINTING. (2014). 3D Printers - How Do They Work ? What is Fused Filament Fabrication (FFF).

ASTM. (2012). Classification of AM process, ASTM 2012.pdf. US: ASTM.

ASTM International. (2013). ASTM International Technical Committee F42 on Additive Manufacturing Technologies, 19428.

Barclift, M. W., & Williams, C. B. (2012). Examining Variability in the Mechanical Properties of Parts Manufactured Via Polyjet Direct 3D Printing, 876–890.

Bemblage, O., & Karunakar, D. B. (2011). A Study on the Blended Wax Patterns in Investment Casting Process. *Proceedings of the World Congress on Engineering 2011*, *1*05-108.

Bird, P. (1995). Metal casting. *Engineering (London)*, *236*(9), 41–42.

Canalys. (2014). 3D printing market to grow to US$16.2 billion in 2018. *Metal Powder Report*, *69*(3), 42.

Cheah, C. M., Chua, C. K., Lee, C. W., Feng, C., & Totong, K. (2005). Rapid prototyping and tooling techniques: A review of applications for rapid investment casting. *International Journal of Advanced Manufacturing Technology*, *25*(3-4), 308–320.

Chen, X., Li, D., Wu, H., Tang, Y., & Zhao, L. (2011). Analysis of ceramic shell cracking in stereolithography-based rapid casting of turbine blade. *International Journal of Advanced Manufacturing Technology*, *55*(5-8), 447–455.

Cotteleer, M. J. (2014). 3D opportunity: Additive manufacturing paths to performance, innovation, and growth. *SIMT Additive Manufacturirng Symposium*, 23.

Das, a. K. (2004). Integrated Product Design Using Rapid Prototyping Technology and Rapid Tooling in Concurrent Engineering Approach. *Materials Science Forum*, *471-472*, 672–676.

Dickens, P. M., Stangroom, R., Greul, M., Holmer, B., Hon, K. K. B., Hovtun, R.,Wimpenny, D. (1995). Conversion of RP models to investment castings.

Ding, Y., Lan, H., Hong, J., & Wu, D. (2004). An integrated manufacturing system for rapid tooling based on rapid prototyping, *20*, 281–288.

Ferreira, J. C., & Mateus, A. (2003). A numerical and experimental study of fracture in RP stereolithography patterns and ceramic shells for investment casting. *Journal of Materials Processing Technology*, *134*(1), 135–144.

Ferreira, J. C., Santos, E., Madureira, H., & Castro, J. (2006). Integration of VP/RP/RT/RE/RM for rapid product and process development. *Rapid Prototyping Journal*, *12*(1), 18–25.

Gouldsen, C. (1998). *Investment Casting Using FDM / ABS Rapid Prototype Patterns*. New York, USA.

Hague, R., & Dickens, P. M. (2015). Improvements in investment casting with stereolithography patterns, *215*, 1–11.

Harun, W. S. W., Safian, S., & Idris, M. H. (2009). Evaluation of ABS patterns produced from FDM for investment casting process. *WIT Transactions on Engineering Sciences*, *64*, 319–328.

Horton, R. a. (2008). Investment Casting. *Casting, ASM Handbook, vol.15*, 563–621.

Jacobs, P. (1995). Rapid tooling. *World Class Design to Manufacture*, *2*(6), 42–50.

Karunakaran, K. P., Shanmuganathan, P. V., Jadhav, S. J., Bhadauria, P., & Pandey, A. (2000). Rapid prototyping of metallic parts and moulds. *Journal of Materials Processing Technology*, *105*(3), 371–381.

Lee, C. W., Chua, C. K., Cheah, (2004). Rapid investment casting: Direct and indirect approaches via fused deposition modelling. *International Journal of Advanced Manufacturing Technology*, *23*(1-2), 93–101.

Levy, G. N., Schindel, R., & Kruth, J. P. (2003). Rapid Manufacturing and Rapid Tooling With Layer Manufacturing (Lm) Technologies, State of the Art and Future Perspectives. *CIRP Annals - Manufacturing Technology*, *52*(2), 589–609.

Li, H., Chandrashekhara, K., Komaragiri, S., Lekakh, S. N., & Richards, V. L. (2014). Crack prediction using nonlinear finite element analysis during pattern removal in investment casting process. *Journal of Materials Processing Technology*, *214*(7), 1418–1426.

Marwah, O. M. F., Sharif, S., Sulaiman, S., Ibrahim, M., & Mohamad, E. J. (2014). Direct Investment Casting Numerical Study for ABS P400 FDM Materials, *660*, 99–103.

Mohd, O., Marwah, F., Sharif, S., & Ibrahim, M. (2012). Direct Fabrication of IC Sacrificial Patterns via Rapid Prototyping Approaches, *6*(5).

Norouzi, Y., Rahmati, S., & Hojjat, Y. (2009). A novel lattice structure for SL investment casting patterns. *Rapid Prototyping Journal*, *15*(4), 255–263.

Omar, M. F. M., Sharif, S., Ibrahim, M., Hehsan, H., Busari, M. N. M., & Hafsa, M. N. (2012). Evaluation of Direct Rapid Prototyping Pattern for Investment Casting. *Advanced Materials Research*, *463-464*, 226–233.

Pal, D., & Ravi, B. (2007). Rapid tooling route selection and evaluation for sand and investment casting. *Virtual and Physical Prototyping*, *2*(4), 197–207.

Patil, R., Kumar, S. M., & Abhilash, E. (2012). Development of Complex Patterns : Scope and Benefits of Rapid Prototyping in Foundries. *International Journal of Engineering and Innovative Technology (IJEIT)*, *1*(4), 68–72.

Polzin, C., Spath, S., & Seitz, H. (2013). Characterization and evaluation of a PMMA-based 3D printing process. *Rapid Prototyping Journal*, *19*(1), 37–43.

Relvas, C., Ramos, a., Completo, a., & Simoes, J. a. (2012). A systematic approach for an accuracy level using rapid prototyping technologies. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *226*(12), 2023–2034.

Sabau, A. S. (2007). Shrinkage Prediction for the Investment Casting of Stainless Steels. *Transactions of American Foundry Society*, *115*(07-042), 1–12.

Shahir Hashim, Azman Hassan, C. S. Y. (2010). *Mechanical , Chemical and Flammability Properties of Abs / Pvc Blends Pm Dr Shahrir Hashim Pm Dr Azman Hassan Chew Sau Yen*. *Mehchanical, Chemical and Flammbility Porperties of ABS/PVC Blends*. Universiti Teknologi Malaysia.

Sivadasan, M., & Singh, N. K. (2013). Use of fused deposition modeling process in investment precision casting – a viable rapid tooling, *1*, 46–49.

Sokovic, M., & Kopac, J. (2006). RE (reverse engineering) as necessary phase by rapid product development. *Journal of Materials Processing Technology*, *175*(1-3), 398–403.

Stratasys. (2011). *ABS P400 MECHANICAL AND THERMAL PROPERTIES*. Dimension-ABS-Model-Material.

Subburaj, K., & Ravi, B. (2008). Computer aided rapid tooling process selection and manufacturability evaluation for injection mold development. *Computers in Industry*, *59*(2-3), 262–276.

Tedds, D. F. B. (2013). The investment casting process. *Institution of Production Engineers Journal*, *33*(12), 663.

Thymianidis, M., Achillas, C., & Tzetzis, D. (2013). Modern Additive Manufacturing Technologies : An Up- to-Date Synthesis and Impact on Supply Chain Design. *International Conference on Supply Chains*.

Träxler, M., Ackermann, J., Juda, M., & Hirsch, D. (2011). Polymethyl methacrylate (PMMA). *Kunststoffe International*, *101*(10), 42–44.

Vasconcelos, P. V., Lino, F. J., & Neto, R. J. L. (2002). The Importance of Rapid Tooling in Product Development. *Key Engineering Materials*, *230-232*, 169–172.

Wang, S., Miranda, a. G., & Shih, C. (2010). A Study of Investment Casting with Plastic Patterns. *Materials and Manufacturing Processes*, *25*(12), 1482–1488.

Wholers, T. (2009), “Wohlers Report 2009: State of Industry”, Wholers Associates Inc., USA.

Wholers, T. (2013), “Wohlers Report 2013: State of Manufacturing Industry”, Wholers Associates Inc., USA.

Wholers, Terry. “Wohlers Report 2014: Additive Manufacturing and 3D Printing State of the Industry.” Wohlers Associates, Inc. 2014.

Wilks Edward S. (2001). Industrial Polymers Handbook, (102), 2396.

Wong, K. V., & Hernandez, A. (2012). A Review of Additive Manufacturing. *ISRN Mechanical Engineering*, *2012*, 1–10.

Wong, a. C Y, and F. Lam. 2002. “Study of Selected Thermal Characteristics of Polypropylene/polyethylene Binary Blends Using DSC and TGA.” *Polymer Testing* 21: 691–96

Yang, J., Shi, Y., Shen, Q., & Yan, C. (2009). Selective laser sintering of HIPS and investment casting technology. *Journal of Materials Processing Technology*, *209*(4), 1901–1908.

Yao, W. L., & Leu, M. C. (1999). Analysis of shell cracking in investment casting with laser stereolithography patterns. *Rapid Prototyping Journal*, *5*(1), 12–20.

Yao, W. L., & Leu, M. C. (2000). Analysis and design of internal web structure of laser stereolithography patterns for investment casting. *Materials & Design*, *21*, 101–109.

Young Won Chang, Nack J. Kim and C. S. Lee, (2007). Study on process of magnesium alloy investment casting. *Materials Science Forum*, 561-565, 101